Fatigue tests were performed transverse to the weld direction for these three different microstructural conditions in four point bending using R=0.1. Test results are illustrated in Figure 8. Considering run out as 10^7 cycles, these results illustrate a 30% increase in run out stress following FSP. These results show the significant benefits of modifying the fusion weld surface using FSP. There was no difference in fatigue life for FSP of the weld toes versus FSP of the entire weld crown. However, each approach offers different benefits. For example, using the small tool to FSP the weld toes, the applied vertical load was considerably less than that for the large tool used to FSP the weld crown. Low loads are important for design of a portable FSP system that will be required to react the FSP loads. However, FSP of the separate toes requires two passes whereas processing of the entire crown can be completed in one pass.

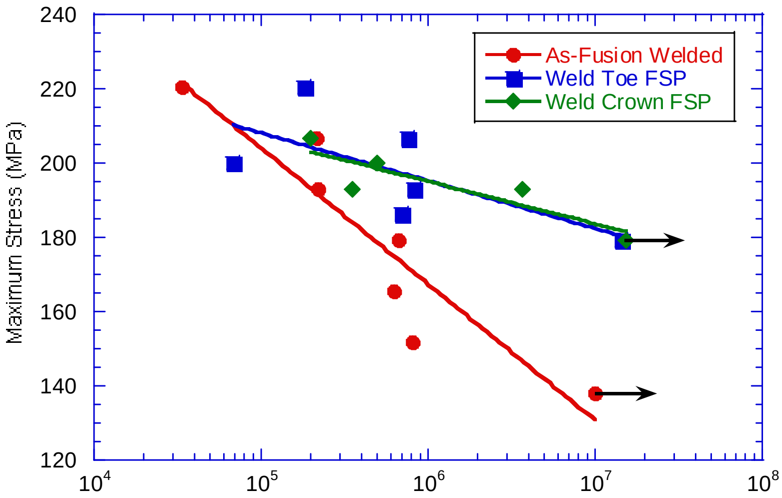

Figure 8 Fatigue life of fusion welded 5083-H321 aluminum and the same alloy following friction stir processing of the weld crown or the weld toes.

Corrosion resistance in a Cu-Mn alloy

Friction stir processing was applied to cast Sonoston, a 52Mn-4Al-3Fe-1.5Ni-39Cu alloy commonly used in a seawater environment. The cast Sonoston microstructure is relatively coarse and suffers from selective de-alloying. Friction stir processing was evaluated to determine if corrosion resistance could be increased by refining the microstructure. As with the NiAl bronze, a variety of microstructures are created by FSP. For FSP material (~0.1mm below the FSP surface) with a refined Widmanstätten microstructure, de-alloying in sea water for 24hrs at –200mV occurred to similar depths to as-cast material. However, for the FSP material, much more severe cracking (delamination parallel to the surface as well as normal to the surface) occurred, and surface layers ‘flaked-off’ readily (Figure 9). Similar depths of de-alloying and cracking behavior were observed for surfaces with mixtures of fine and coarse plates towards the edges of the FSP zone just beneath the FSP surface (Figure 10). Specimens with surfaces exhibiting a very fine-grained microstructure (~4mm below the original FSP surface) were also de-alloyed and cracked to a depth of about 400μm after exposure to sea water for 24hrs at –200mV (Figure 11).

After stress-relieving heat-treatments, the depths of de-alloying for the refined FSP microstructures were substantially reduced compared with the coarse as-cast structure. For the fine Widmanstätten microstructure just below the FSP surface, stress-relieving for various times and temperatures showed that 8hrs at 500ºC or 24hrs at 600ºC were required for improved corrosion resistance (Figure 12). For specimens with the fine-grained region at the surface, 24hrs at 450ºC was sufficient to dramatically decrease the depth of de-alloying (to only 5-10μm) (Figure 13). The stress-relief heat-treatments appeared to have little effect on the depth of de-alloying for the coarse as-cast microstructures.

The stress-relieved and refined FSP microstructures have shallower de-alloyed layers than the coarse as-cast microstructures because de-alloying is confined to Mn-rich regions that are connected to the surface, and such regions occur to shallower depths following FSP. However, when high residual tensile stresses are present (created by FSP), SCC occurs through the Cu-rich areas, thereby allowing the environment to penetrate to Mn-rich areas not otherwise connected to the surface, so that de-alloying continues to occur. A somewhat lower stress-relief temperature for the fine-grained microstructure compared with the refined Widmanstätten microstructure is required possibly because residual stresses were lower at greater depths below the FSP surface or because the fine-grained microstructure is inherently more resistant to SCC (or both).

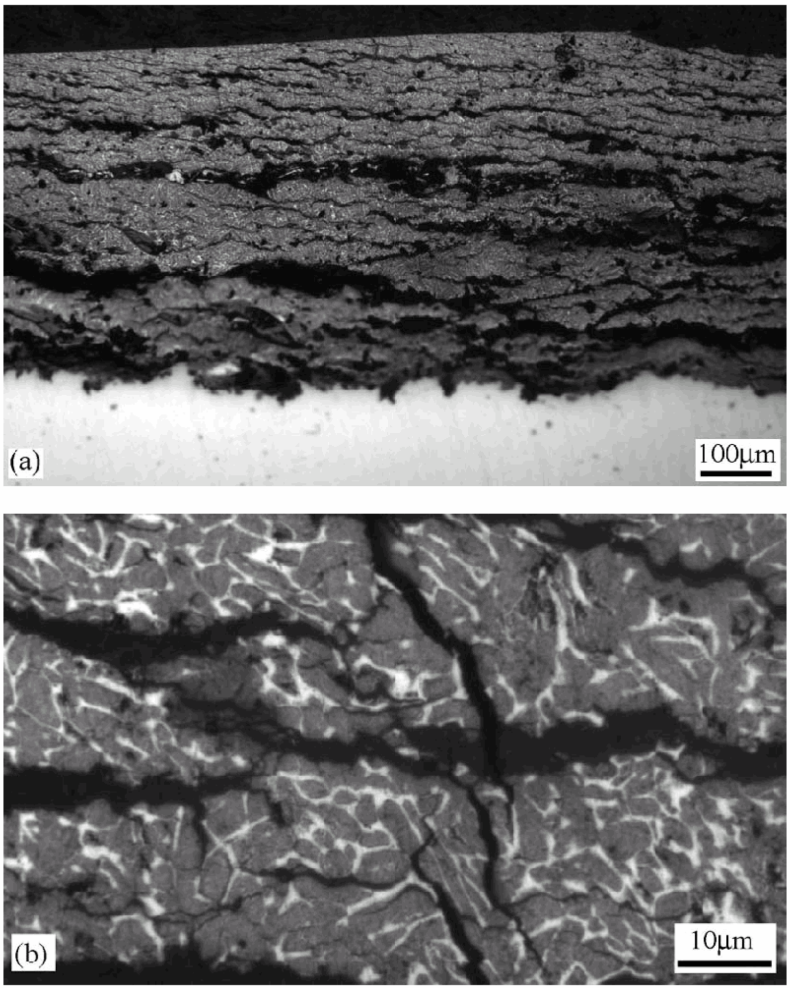

Figure 9 Optical micrographs of *unetched sections* normal to the surface of specimens with the CBN-FSP fine Widmanstätten microstructure dealloyed for 24hrs at –200mV in sea water, (a) at low magnification showing heavily cracked de-alloyed layer, and (b) at high magnification showing de-alloyedMn-rich areas and uncorroded Cu-rich areas.

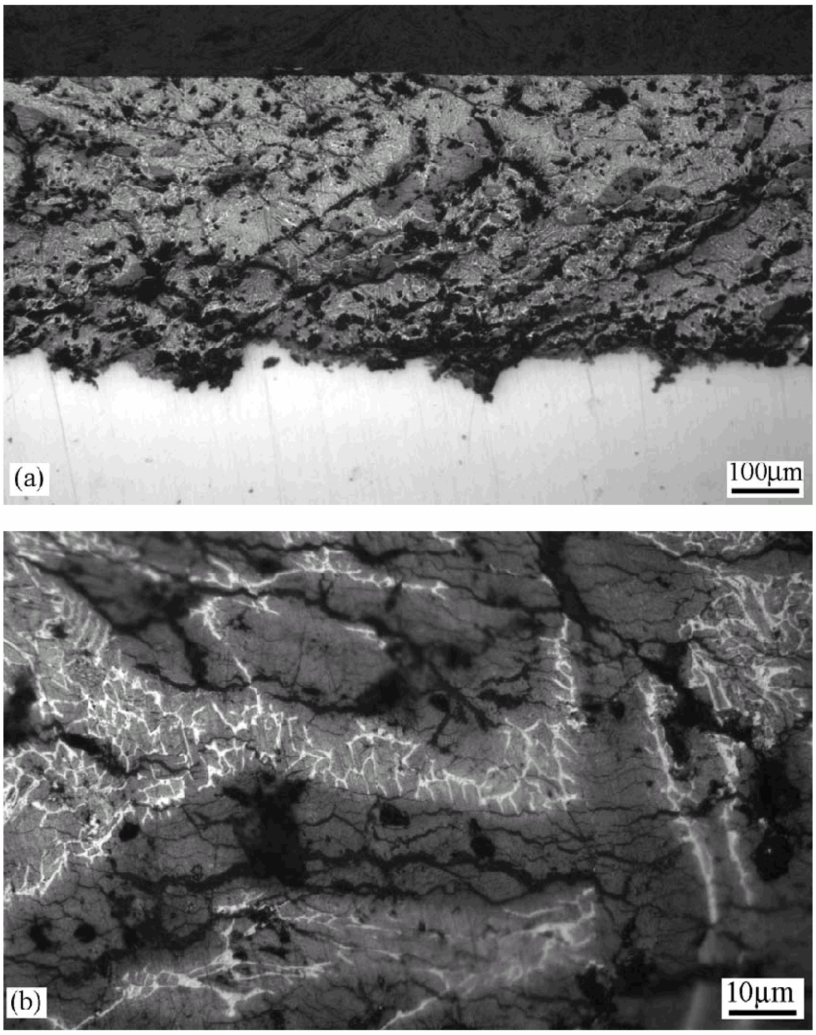

Figure 10 Optical micrographs of *unetched sections* normal to the surface of specimens with the CBN-FSP fine and coarse Widmanstätten, de-alloyed for 24hrs at –200mV in sea water (a) at low magnification, and (b) at high magnification.

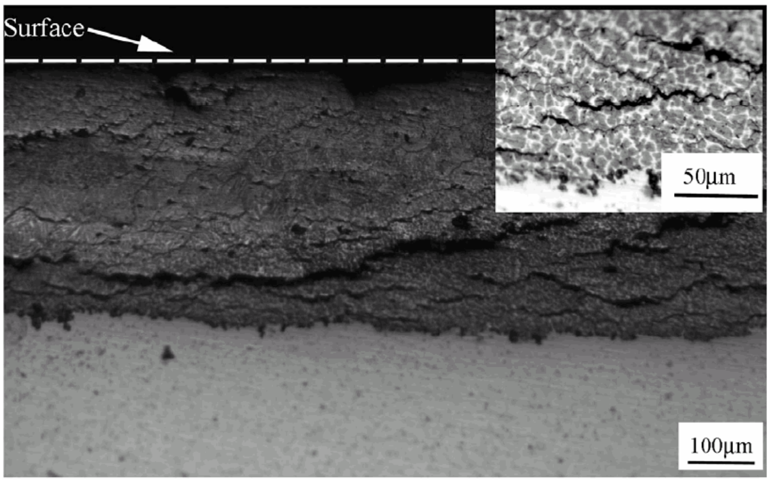

Figure 11 Optical micrograph of *unetched section* normal to the surface of specimen with the CBN-FSP fine grained microstructure (4mm below FSP surface) after de-alloying for 24hrs at –200mV, inset shows high magnification view.

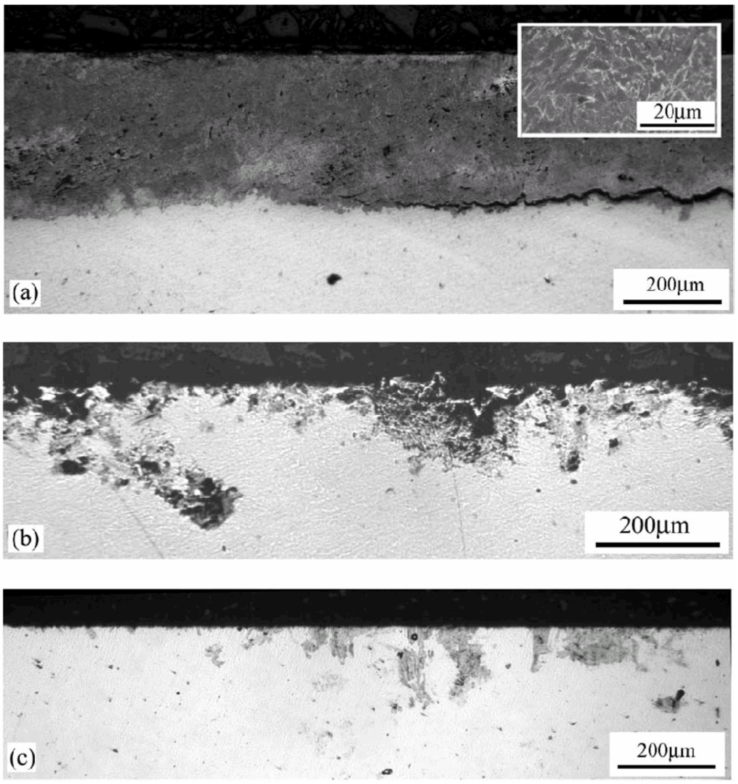

Figure 12 Optical micrographs of *unetched sections* normal to surface with a CBN-FSP fine Widmanstätten structure de-alloyed for 24hrs at –200mV (versus saturated calomel electrode) specimens stress-relieved for: (a) 24hrs at 450ºC, (b) 8hrs at 500ºC, and (c) 2hrs at 600ºC.

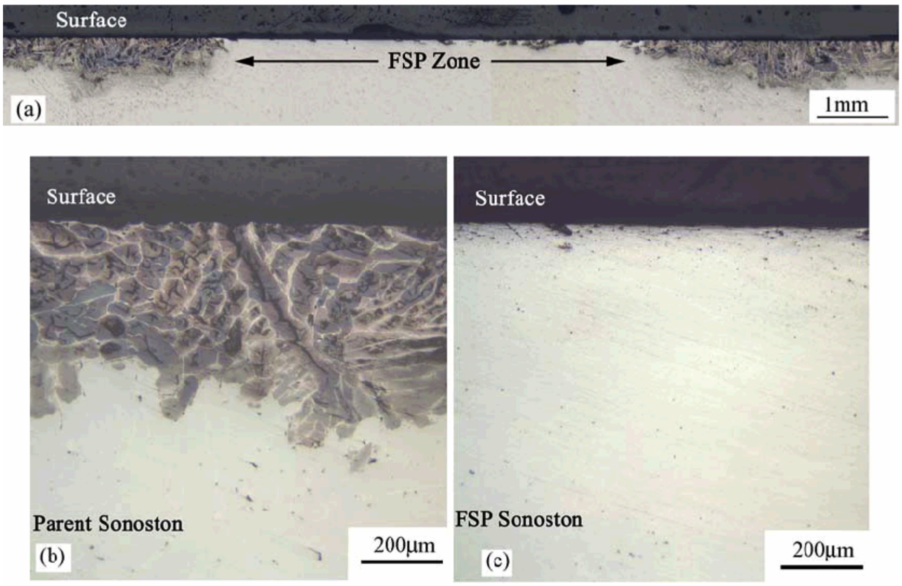

Figure 13 Optical micrographs of unetched sections normal to surfaces with CBN-FSP fine-grained globular structures, and adjacent as-cast structures de-alloyed for 24hrs at –200mV (versus SCE) for specimens stress-relieved for 24hrs at 450ºC. (a) FSP zone and adjacent as-cast zones at low magnification and (b), (c) FSP zones and adjacent zones at a higher magnification.

Room temperature bending of 25mm thick 2519 aluminum

Friction stir processing can also be used to enhance the formability of aluminum alloys. A number of authors have demonstrated exceptional superplasticity following FSP.[12-14] However, superplastic forming requires high temperature and the aluminum is friction stir processed through the entire sheet thickness. A different surface engineering application for FSP is the creation of room temperature formability in thick aluminum plate. For this application of FSP, a large surface area is friction stir processed. This is accomplished by rastering the FSP tool forward and back until the surface area that subsequently experiences high tensile stresses during bending has been processed. Typically, the FSP tool is moved ½ pin diameter to the advancing side of the previous pass. FSP provides three changes including 1) creation of a fine grain microstructure with increased ductility, 2) the surface is essentially annealed without significantly changing properties of the unprocessed metal, and 3) any superficial surface cracks associated with plate processing are removed. Figure 13 illustrates an example whereby the FSP tool pin penetrated 6 mm into a 25 mm thick 2519 aluminum plate. Following FSP, the plate was bent at room temperature to 80º without cracking. For comparison, as-received plate was bent using the same procedure and failed after approximately 30º. This FSP/bending process could replace conventional techniques where a structure is fabricated by fusion welding thick plates into a complex shape.

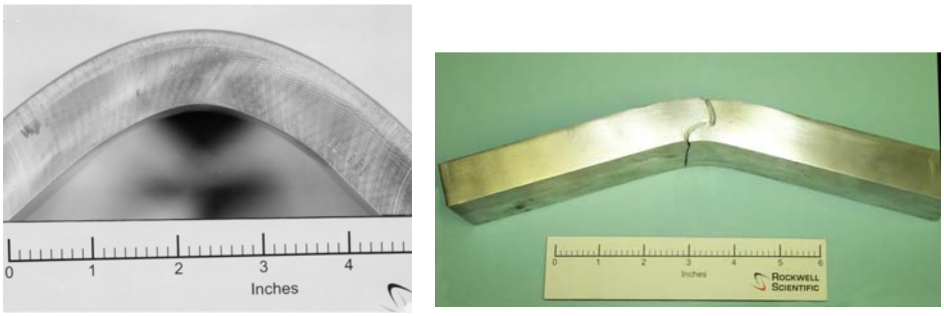

Figure 13 a) Room temperature bending of 25 mm thick 2519 aluminum plate to 80º following FSP to a depth of 6 mm, and b) fracture of as-received plate at a 30º bend.

FSP and low plasticity burnishing to increase corrosion fatigue strength

Friction stir processing locally creates a high temperature, short time, thermal transient. Like any high temperature process, this can result in tensile residual stresses on the structure's surface. To change FSP tensile residual stresses to compressive, low plasticity burnishing (LPB) has been explored. Figure 14 is a photograph of LPB in operation on a CNC milling machine. Briefly, LPB produces a layer of compressive residual stress of high magnitude and depth with minimal cold work.[15-18] LPB is usually performed using a single pass of a smooth free rolling ball under a normal force sufficient to plastically deform the surface of the material. Hertzian loading creates a layer of compressive residual stress to a depth as much as 4 mm. The ball is supported in a fluid bearing with sufficient pressure to lift the ball off the surface of the retaining spherical socket. The ball is in solid contact only with the surface to be burnished and is free to roll on the surface of the work piece. LPB parameters were optimized for the 2219-T8751 friction stir weld, i.e., to impart the greatest depth and magnitude of residual stress with minimal cold work. For this work, the LPB was performed in the direction of the weld using multiple passes adjacent to and in the weld.

Low plasticity burnishing produced compressive residual stresses as high as –450 MPa both parallel to and perpendicular to the weld direction. This compares to a tensile residual stress greater than +200 MPa in the as-friction stir welded sample. Figure 15 illustrates fatigue and corrosion/fatigue results for friction stir welded 2219 aluminum in the following conditions: 1) milled, 2) milled + LPB, 3) milled + 100 hours in a salt environment, and 4) milled + LPB + 100 hours in a salt environment. LPB increased the endurance limit by nominally 60% in salt corroded FSW specimens. Specimens that were LPB and salt corroded had the same nominal fatigue strength as samples that were LPB processed without corrosion indicating that LPB process eliminated any fatigue debit from salt fog corrosion.

Figure 14 Low plasticity burnishing of a FSP 2219 aluminum plate.

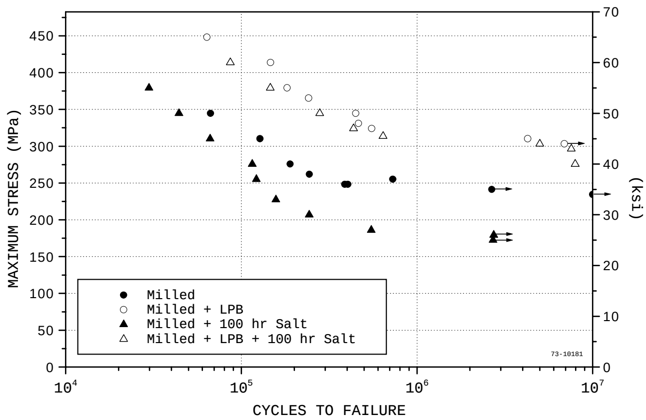

Figure 15 Fatigue and corrosion/fatigue test results fro friction stir welded 2219-T8751 aluminum with and without low plasticity burnishing.

Acknowledgements

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